THE DRAGONFLY GALAXY III. AN IMPOSTER RADIO GALAXY IN THE HIGH REDSHIFT UNIVERSE

Research Thesis
Presented in partial fulfillment of the requirements
for graduation with research distinction in Astronomy and Astrophysics
in the undergraduate colleges of The Ohio State University
by

Sophie Lebowitz
The Ohio State University
Thesis Advisor: Dr. Donald Terndrup, Department of Astronomy
Project Advisor: Dr. Bjorn Emonts, The National Radio Astronomy Observatory

April 27, 2020

1 Chapter 1

1.1 Introduction to the Thesis

In June of 2018, I began a Research Experience for Undergraduates (REU) at the National Radio Astronomy Observatory (NRAO) under the supervision of Dr. Bjorn Emonts. What started as an eight week project extended into a two year-long investigation of a unique system in the distant universe called the Dragonfly Galaxy (MRC 0152-209). The Dragonfly Galaxy, named after its insect-like appearance in an image taken by Hubble (Fig. 1 - left), is a system of three, potentially merging galaxies. The Dragonfly Galaxy, with z=1.92, was for a long time missed by traditional high redshift surveys, which would begin their search at z=2. After its identification by Pentericci et al. [2000, 2001] it became apparent the Dragonfly Galaxy was a multi-faceted system undergoing extreme evolutionary changes. Initial studies revealed the Dragonfly Galaxy to be the most infrared luminous radio galaxy at z=2, and estimated a large star formation rate of roughly 3000 $M_{\odot}$ yr^{-1} [Drouart et al., 2014]. The first radio investigations into the system revealed a powerful radio source $\sim$10 kpc in size [Pentericci et al., 2000]. Dr. Emonts and his team conducted follow-up observations with the Australian Telescope Compact Array (ATCA) and Atacama Large Millimeter Array (ALMA) and found that the system likely consisted of three galaxies in the early stages of merging, and contained a large reservoir of cold molecular gas [Emonts et al., 2015a,b]. As a radio-loud, high-z, triple merger system containing a powerful radio jet and large amounts of gas displacement, the Dragonfly Galaxy presents an unusual snapshot in this early epoch of galaxy formation that may provide insight into the nature of high-z radio galaxies and the formation of massive galaxies.

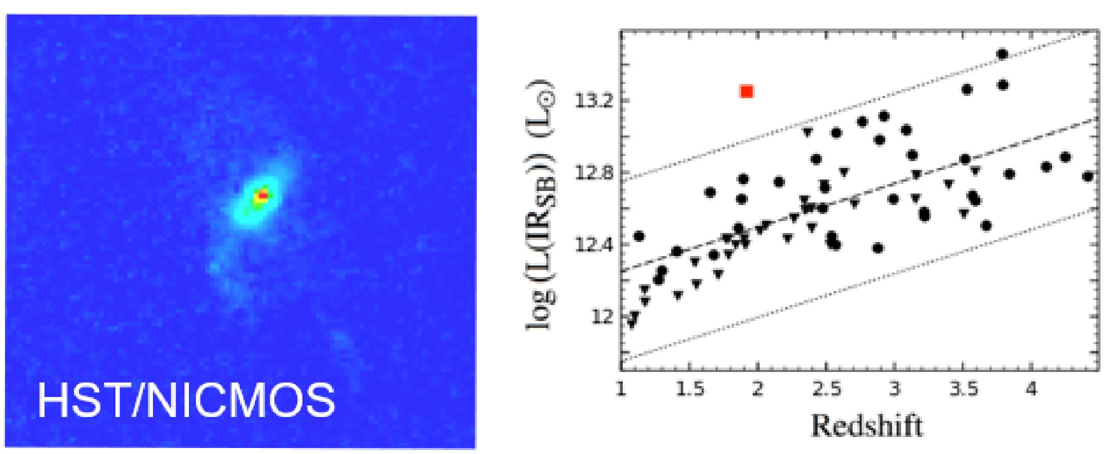

Figure 1: Left: HST/NICMOS F160W image from Pentericci et al. [2001]. Right: Plot of starburst IR luminosity plotted against redshift adapted from Drouart et al. [2014]. The red square represents the Dragonfly Galaxy. The black symbols are other high-z radio galaxies (dots are detections, triangles are upper limits).

The first in depth radio study on the Dragonfly Galaxy was done by Dr. Emonts and his team using ATCA. Their results are detailed in Emonts et al. [2015a]. The paper describes CO (1-0) observations that showed a general alignment of CO (1-0) with the host galaxy, which also appeared to coincide with the tidal features seen in the optical image (Fig.1 - left). Interestingly, the CO (1-0) gas in the tidal regions was found at higher velocities than near the host galaxy and appeared to be aligned with the radio source. The study proposed a model in which the radio source was a propagating radio jet that is influencing the gaseous environment of the galaxy and triggering the alignment of the cold molecular gas along the radio axis. A second study by Dr. Emonts and his team complemented the CO (1-0) observations with ALMA Cycle 2 observations of CO (6-5) [Emonts et al., 2015b]. CO (6-5) is a more highly excited transition than CO (1-0) making it an excellent tracer of denser, warmer gas found in the Active Galactic Nucleus (AGN) and starburst regions of a galaxy. The short six minute observation of CO (6-5) in the system revealed an incredible rate of molecular gas redistribution of at least $\dot{M}\sim1200\pm500\ M_{\odot}\ yr^{-1}$ between two of the merging galaxies [Emonts et al., 2015b]. This was hypothesized to be a result of either the gravitational effects of the merger or starbursts/AGN-driven outflows. The initial results of the observation led to a proposal for follow-up observations with the Very Large Array (VLA) in May of 2015 and ALMA Cycle 4 in 2017.

The ALMA Cycle 4 CO (6-5) observations and high resolution observations by the VLA of the Dragonfly Galaxy provided the foundations for my summer research project at NRAO and continued thesis work. The project goal was to further study the gas kinematics in the system, and determine if the high velocity, high excitation gas seen by Emonts et al. [2015b] was a result of tidal forces from merging or outflows from an AGN or starbursts. The data had already been calibrated by our team, which allowed me to start directly on imaging the data. The first half of my internship was primarily devoted to using the Common Astronomy Software Applications (CASA) to convert the data into 2D images and 3D data cubes. After extracting the best images, I worked with Dr. Emonts to analyze and interpret the CO (6-5) kinematic data from ALMA and the high resolution VLA data of the radio source. I then combined the previous data from ALMA Cycle 2 with ALMA Cycle 4 data to provide a more complete picture of the system. The initial results clearly indicated tidal forces were the dominant factor driving the high rates of gas displacement, however the new data also indicated new features never before detected including a radio hot spot located near the companion galaxy and a potential AGN outflow.

The results from the eight week project were presented by me at the 233th AAS meeting in January of 2019 [Lebowitz, 2019], but the conclusion of the summer project still left several unanswered questions about the fundamental nature of the Dragonfly Galaxy. Sponsored by the National Astronomy Consortium, I joined Dr. Jason Prochaska's team at University of California Santa

Cruz in the following October, to conduct follow-up observations with the Keck Telescope to try to learn more about the larger gaseous environment of the system. The results from my project at NRAO, Keck observations, and ongoing thesis work have culminated in a paper on the Dragonfly Galaxy in which I am the lead author. The paper is nearing completion of its first draft and will soon be sent to our collaborators for review. Chapter 2 of the thesis contains the current snapshot of the collaborative paper. My contributions towards data collection and analysis are detailed in the paragraph below. The section titled 'Contributions' details the contributions of each group member towards the collaborative paper (Chapter 2).

1.2 Imaging, Observation, and Data Analysis

The Common Astronomy Software Applications (CASA) was used to image and analyze the ALMA and VLA data. ALMA and VLA observations were conducted by the science staff and reduced by Bjorn Emonts. I conducted the primary imaging of the radio data using the function 'tclean' to convert the ALMA cycle 2 and 4, and VLA data files to continuum and line spectrum images. Further programming tasks in the CASA software aided our analysis of the data. I used the CASA tasks 'imsmooth' and 'hanningsmooth' to smooth the data in RA, Dec, and frequency in order to pick up more signal to noise. I used 'immoment' to create Moment 0 (integrated spectrum), 1 (velocity fields), and 2 (velocity dispersion) kinematic maps of CO emission.

I joined Dr. Joe Burchett to conduct observations on the Dragonfly Galaxy as a part of a larger survey with the Keck Cosmic Web Imager (KCWI). Observations were conducted on October 5th and 6th at a central wavelength of 420nm. The data was reduced by Dr. Burchett. I then used QFits view for the basic analysis of the Keck data to obtain emission line spectra for the system.

1.3 Contributions

The drafting of the paper based on the current results began in fall semester of 2019 as a collaboration between Dr. Emonts at NRAO, Dr. Terndrup at OSU, and I. My primary contributions to the paper include creating and interpreting the ALMA and VLA images (Fig. 2-4 and Fig. 7), conducting the initial analysis of the Keck spectroscopy (2.3.3), and drafting the abstract, results (2.3), discussion (2.4), and conclusion (2.5). Dr. Emonts wrote the majority of the introduction (2.1) and methods section (2.2). Dr. Emonts also assisted my sections through revision, improving the presentation of the figures, and helping to fill in missing gaps from the initial data analysis from two years ago.

2 Chapter 2

Abstract

The Dragonfly Galaxy (MRC 0152-209), the most infrared-luminous radio galaxy at redshift $z = 2$, is a unique system of merging galaxies containing a powerful radio source and large rates of gas displacement. We present sub-kpc resolution data from the Atacama Large Millimeter Array (ALMA) and the Very Large Array (VLA) of the emission of carbon monoxide (6-5), dust, and synchrotron continuum, and combine this with new spectra from the Keck Cosmic Web Imager to study the radio-loud AGN and host galaxy. We find that the Dragonfly Galaxy consists of two galaxies with rotating disks that are 4 kpc apart. Our VLA data suggest that the radio jet brightens when it hits the disk of the secondary galaxy. While the Keck spectra shows the presence of a powerful AGN from rest-frame UV lines, the Dragonfly Galaxy appears to be classified as a powerful radio galaxy as the result of this jet-disk interaction, which boosts the radio flux into the regime of high-z radio galaxies. Despite the high AGN and starburst activity, we do not find evidence for molecular outflows at the location of the radio hot-spot or associated with the secondary galaxy. A potential molecular outflow is seen on larger scales around the radio host galaxy, but overall the bulk of the gas displacement in the Dragonfly Galaxy appears to be driven by gravitational effects of the ongoing merger.

2.1 Introduction

For decades, high redshift radio galaxies (HzRGs; $P_{500\,\mathrm{MHz}} > 10^{27}$ W Hz^{-1}) have served as excellent laboratories for studying the early formation and evolution of galaxies. The bright synchrotron emission from their powerful, steep-spectrum radio sources has long been used as a beacon for tracing the faint optical signatures of massive galaxies and proto-clusters [e.g., Roettgering et al., 1994, Chambers et al., 1996, Carilli et al., 1997, Pentericci et al., 2000, see also review by Miley and De Breuck 2008]. High redshift radio galaxies occupy the high end of galaxy masses [e.g., Pentericci et al., 2001, Seymour and SHzRG Collaboration, 2007, De Breuck et al., 2010, Rocca-Volmerange et al., 2013]. They also possess characteristics that can give valuable insight into the process of galaxy evolution, such as high rates of star formation and Active Galactic Nuclear (AGN) activity [e.g., Barthel et al., 2012, Drouart et al., 2016, Wilkes et al., 2013], and jet-driven gas outflows [e.g., Villar-Martín et al., 1999, Nesvadba et al., 2017]. High-z radio galaxies are often found in overdense regions, as expected from the progenitors of giant elliptical galaxies that occupy the centers of galaxy clusters [e.g., Pentericci et al., 1997, Venemans et al., 2007, Hatch et al., 2009, Galametz et al., 2012, Wylezalek et al., 2013, Dannerbauer et al., 2014]. These properties have attributed high-z radio galaxies to represent the most active episodes in the early evolution of massive galaxies. However, more recent studies reveal that many high-z radio galaxies may be on the way to quenching [e.g., Man et al., 2019, Falkendal et al., 2019]. Accurate techniques for determining the complex spectral energy distributions [e.g., Drouart and Falkendal, 2018] are starting to reveal that many of the radio host galaxies may even fall below the main sequence of star-forming galaxies [Falkendal et al., 2019].

The Dragonfly Galaxy, MRC 0152-209, is a radio galaxy at $z = 1.92$ that shows extreme characteristics, even for a high-z radio galaxy. Its starburst infrared luminosity is in the regime of Hyper-Luminous Infra-Red Galaxies (HyLIRGs; $L_{\rm IR} \geq 10^{13}\, L_{\odot}$), which is roughly an order of magnitude higher than other HzRGs at $z \sim 2$ [Drouart et al., 2014, Falkendal et al., 2019]. This reflects star formation rates that were initially estimated at SFR $\sim$ 3000 M$_{\odot}$ yr^{-1} [Drouart et al., 2014], but later corrected to SFR $\sim$ 2000 M$_{\odot}$ yr^{-1} [Falkendal et al., 2019]. Imaging done with the Hubble Space Telescope (HST) Near Infrared Camera and Multi-Object Spectrometer (NICMOS) showed that the Dragonfly appears to be a merger system [Pentericci et al., 2001]. The radio source in the Dragonfly Galaxy is $\sim$10 kpc in size, and only slightly resolved in existing radio images at 4.5 and 8.2 GHz [Pentericci et al., 2000].

The Dragonfly Galaxy also contains a large mass of cold molecular gas, $M_{H_2} \sim 5 \times 10^{10}$ ($\alpha_{\rm CO}$=0.8) M$_{\odot}$ [Emonts et al., 2011]. This is derived from a CO (1-0) luminosity that is at the high end of what is found in high-z radio galaxies [Emonts et al., 2014]. The CO (1-0) emission revealed a molecular gas reservoir that is spread across scales of $\sim$60 kpc, likely reflecting widespread tidal debris of cold gas [Emonts et al. 2015aa]. Observations of CO (6-5) with the Atacama Large Millimeter/submillimeter Array (ALMA) in Cycle 2 showed that the Dragonfly Galaxy is a system of three merging galaxies with one containing a powerful radio jet [Emonts et al. 2015bb]. This work revealed that large amounts of cold molecular gas were being displaced between two of the merging galaxies at a rate between 1200 and 3000 M$_{\odot}$ yr^{-1}, which matches the star-formation rate in this system. However, these Cycle 2 data could not distinguish whether the gas kinematics in the Dragonfly Galaxy were caused by gaseous outflows, or by gravitational interaction between two rotating disk galaxies [Emonts et al. 2015bb].

In this paper, we present new, sub-kpc resolution data from the Atacama Large Millimeter/submillimeter Array (ALMA) and the NFS's Karl G. Jansky Very Large Array (VLA) of the emission of carbon monoxide (6-5), dust, and synchrotron continuum. This allows us to map in detail the radio source and host galaxy, to study the unusual properties of this high-z radio galaxy. We will also investigate what drives the rapid displacement of molecular gas in this system, tidal forces from merging or outflows driven by the radio jets or star formation. Our work reveals that gravitational effects of two merging disk galaxies appear to be the dominant factor in driving the molecular gas displacement, not AGN-feedback.

Throughout this paper, we assume the following cosmological parameters: $\mathrm{H_0} = 71$, $\Omega_\mathrm{M} = 0.3$ and $\Omega_\Lambda = 0.7$, which at $z = 1.9212$ corresponds to 8.3 kpc/arcsec and a luminosity distance of $D_\mathrm{L} = 14583$ Mpc [Wright, 2006].

2.2 Methods

2.2.1 ALMA

The ALMA Cycle 4 observations were conducted on 9 and 17 August 2017 for 1.2 hour on-source with 45 antennas with baselines up to ∼3.5 km. We configured the four spectral windows to cover two 4 GHz bands, one that includes the redshifted CO(6-5) line (235.8−239.6 GHz) and the other including only continuum (251.2−255.0 GHz). The data were calibrated using the ALMA calibration pipeline that is included in the Common Astronomical Software Applications (CASA) version 4.7.2 (McMullin et al. 2017; CASA Team et al. in prep.), by means of running the script that was supplied with the data by the North American ALMA Science Center (NAASC). Subsequent imaging was done manually using CASA version 5.3.0. For the line data, we subtracted the continuum in the (u,v)-domain by fitting a straight line to the line-free channels. We then combined our Cycle 4 data with 6 min of ALMA Cycle 2 observations taken at the same frequency but in a more compact configuration (baselines ≥17m; [Emonts et al., 2015b]). Imaging and deconvolution was done using a robust 0.5 weighting scheme, resulting in an image resolution of 0.12×0.08 arcsec (PA 80°)). The line data were imaged with a spectral resolution of 15 $\mathrm{km\,s^{-1}}$ for a single channel, resulting in a root-mean-square (rms) noise of 0.24 $\mathrm{mJy\,beam^{-1}\,chan^{-1}}$.

2.2.2 VLA

The VLA observations were conducted on 29 May 2015 in BnA-configuration, 5 and 13 August 2015 in A-configuration, and 30 December 2017 in B-configuration (projects VLA/15A-316 and VLA/17B-444). The total on-source time was 3.3 hours. The observations were centred at 43 GHz and used an effective bandwidth of 7.5 GHz. We used calibrator J2253+1608 for calibrating the bandpass response, J0204-1701 at 4.4° distance from our target for calibrating the complex gains every 60-70 seconds, and 3C147 for applying the absolute flux scale.

A standard data reduction and analysis was performed using CASA version 5.1.1 for calibrating the A- and BnA-configuration data, and CASA version 5.3.0 for calibrating the B-configuration data and subsequent imaging of the combined data. We used the multi-frequency synthesis method with a robust weighting scheme to create continuum image with a resolution of 0.08×0.05 arcsec. The data were cleaned, but the signal was not strong enough to perform a self-calibration. This means that low-level artifacts due to phase errors persist in the image.

2.2.3 Keck

The Keck observation was conducted October 5th and 6th, 2018 using the Keck Cosmic Web Imager at central wavelength 420nm. The KCWI large slicer and BL grating was used to cover the effective wavelength range of $345 - 525$ nm, or $118 - 180$ nm in the rest frame. The total exposure time was 50 minutes, divided into five dithered exposures of 10 minutes each. The data were reduced in a standard way using the KCWI pipeline.

2.3 Results

2.3.1 Molecular Gas

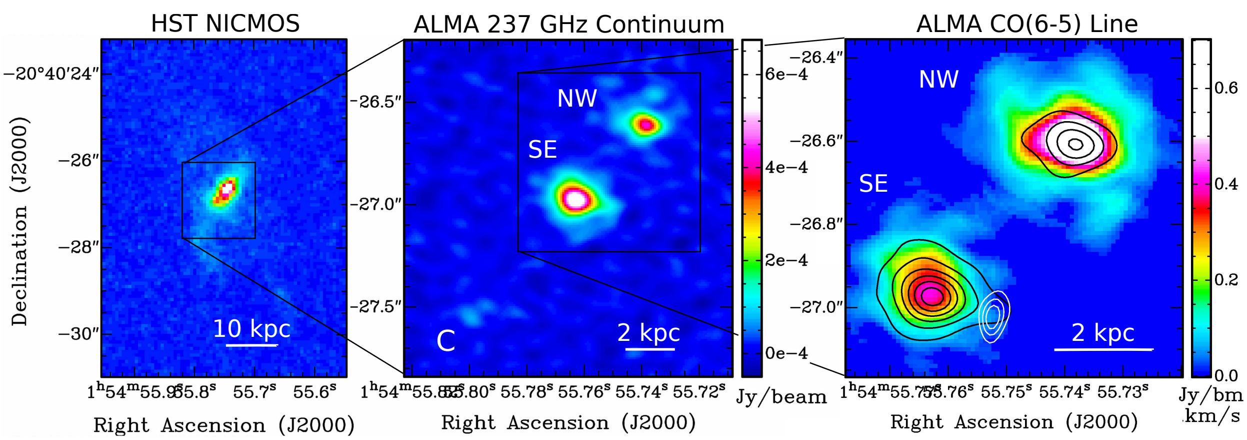

Figure 2: Left: HST/NICMOS F160W Image of Dragonfly Galaxy (z=1.92) [4], Middle: 237 GHz (692 GHz rest frame) ALMA continuum emission from dust in the inner 13 kpc. Right: Total Intensity map of ALMA CO (6-5) emission in the inner 7 kpc. The black contours are the 237 GHz ALMA dust continuum from the middle plot. Contour levels start at 0.1 mJy beam^{-1} and increase in steps of 0.1 mJy beam^{-1}. The white contours are the 39 GHz (115 GHz rest frame) VLA synchrotron emission of a radio hot spot (see Fig. 3 and Sect. 2.3.2). Contour levels start at 0.4 mJy beam^{-1} and increase in steps of 0.4 mJy beam^{-1}.

Figure 2 (left) shows an HST image of the Dragonfly Galaxy. On a scale of several tens of kpc, the HST image shows prominent tidal features that were previously described in Emonts et al. (2015a). Figure 2 (middle) shows the ALMA 237 GHz continuum image, which reveals three components. Components NW and SE appear in the center of the Dragonfly system and were previously detected by [Emonts et al., 2015b]. Component C was previously detected in CO (6-5) but not the 237 GHz continuum [Emonts et al., 2015b]. These new observations reveal a peak flux density of 70 μJy beam^{-1} for component C. Figure 2 (right) shows a total intensity map of ALMA CO (6-5) emission in the central ~8 kpc. The ALMA data clearly show that the Dragonfly consists of two central galaxies, NW and SE, which are separated by ~4 kpc. Component C could be a third galaxy (see also Emonts et al. 2015b).

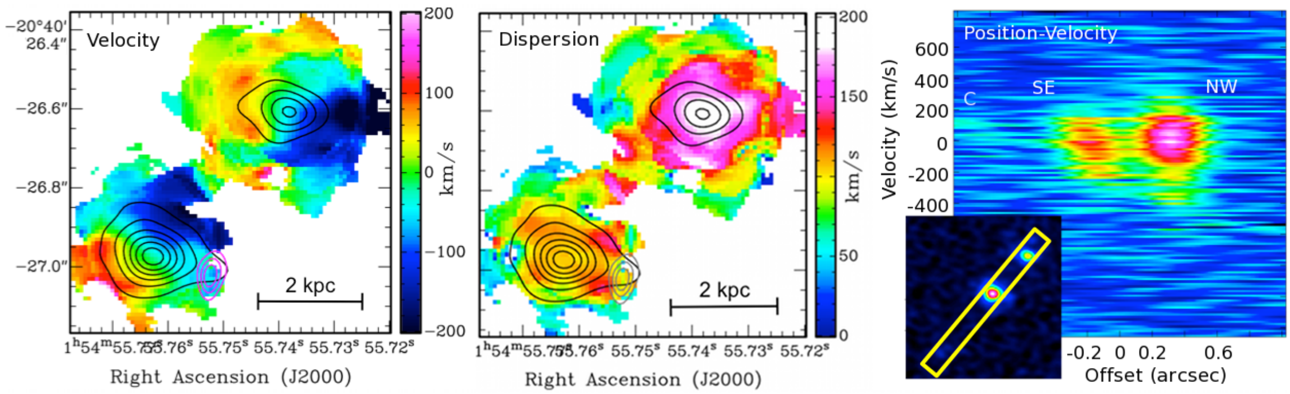

Figure 3: Left: Moment 1 Velocity Map of CO (6-5), Middle: Moment 2 Velocity Dispersion Map of CO (6-5), The contours show the ALMA and VLA continuum data from Fig. 1. Right: Position Velocity Map (Imsmoothed to resolution of 300 mas) taken along position angle shown as yellow rectangle in bottom right-hand corner.

Figure 3 (left) shows a moment-1 velocity map of CO (6-5). Both NW and SE possess distinct regions of redshfited and blueshifted gas, indicative of rotating disks. The two disks are connected by a tidal bridge of gas with a large velocity gradient. This bridge of CO emission between the galaxies is also visible in the position-velocity plot with the pseudo-slit taken along the radio axis (Fig. 3 - right). The moment-2 velocity dispersion plot (Fig. 3 - middle) shows that the molecular gas in the bridge has a high velocity dispersion, with $\sigma_{CO} \leq 170$ km/s.

2.3.2 Radio-loud AGN

The radio source that classifies the Dragonfly Galaxy as a high-redshift radio galaxy is shown in Figure 4 (left). The contours of the radio jet detected by the VLA at 8 GHz are overlaid on our new high-resolution VLA image at 43 GHz. The alignment of the central axis of the 8 GHz radio source with the NW galaxy suggests that NW is the host of the radio source (Emonts et al. 2015). This is consistent with the high velocity dispersion found in the center of NW indicative of an AGN. At 43 GHz, the high resolving power of the VLA left too little surface brightness sensitivity to pick up the lobes of the jet, but a bright spot was detected on the western edge of the SE galaxy. This bright spot is aligned along the radio axis and has a flux density of 1.8 ±0.2 mJy. The northern 8 GHz lobe shows a tentative and apparently unresolved 43 GHz counterpart at a 5.5σ level, with a peak flux density of 0.13 mJy beam^{-1}.

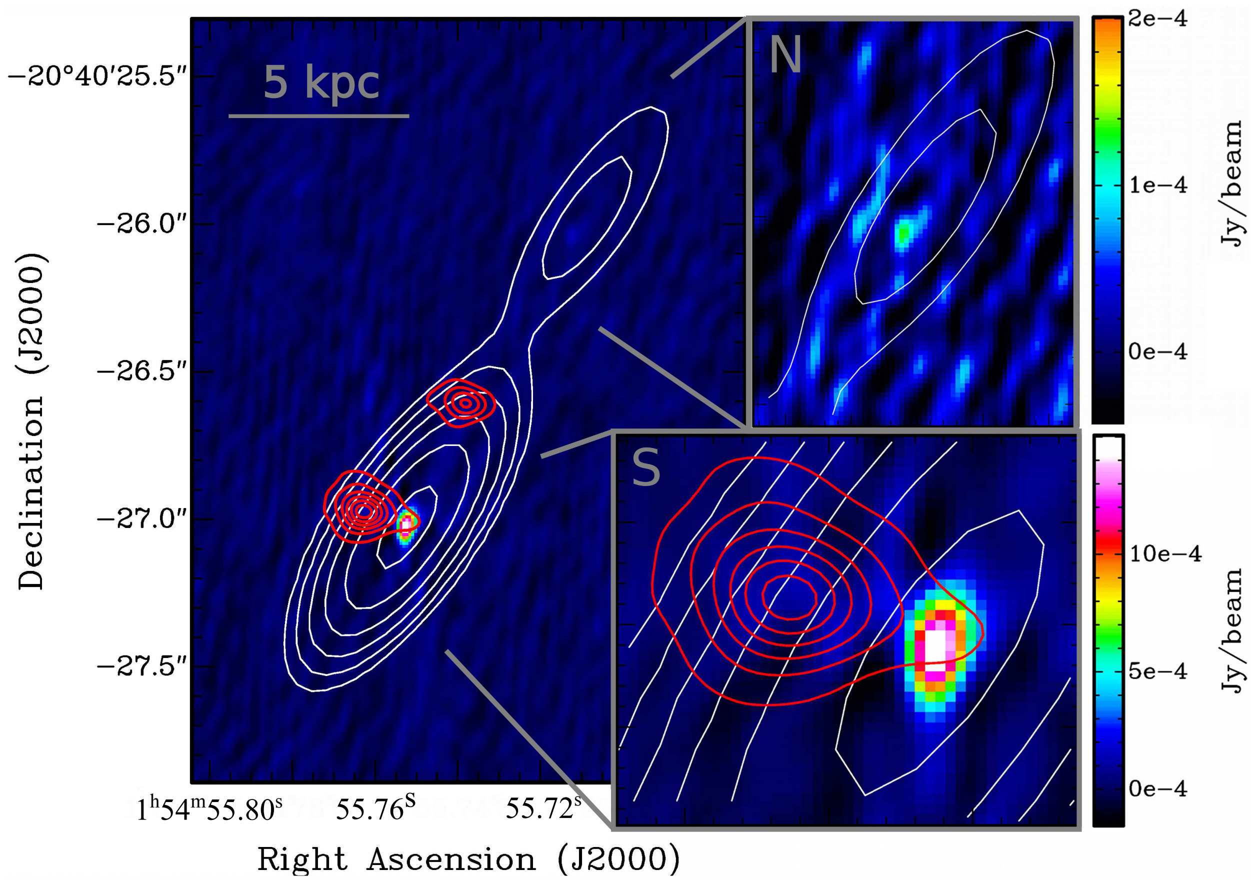

Figure 4: VLA 43 GHz Continuum Image of the bright radio hot-spot located on right edge of the SE galaxy. The white contours show previous lower resolution VLA data of the radio source taken at 8 GHz [Pentericci et al., 2000]. Contours start at 1 mJy beam^{-1} and increase by a factor of 2. Self-calibration of the 8 GHz data could have affected its positional accuracy, so we shifted the 8 GHz radio continuum by 0.09 arcsec to create the best possible overlay with the 43 GHz continuum. The red contours show the ALMA 237 GHz dust continuum from Fig. 2. The insets on the right show the bright 43 GHz hot-spot in the southern lobe (bottom) and a tentative weak and unresolved 43 GHz counterpart to the northern lobe (top).

2.3.3 Keck Results

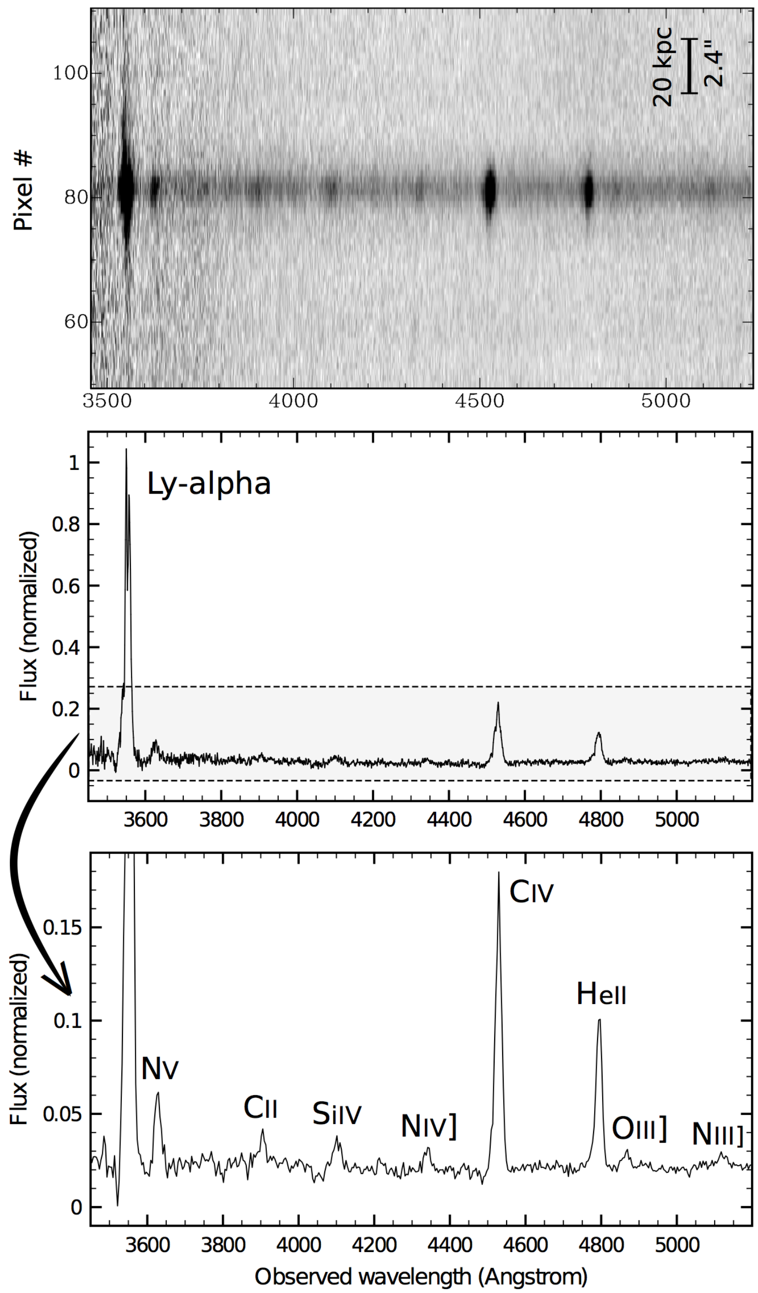

Figure 5: Keck spectroscopy. Top: 2D spectrum taken with an 6.75″ wide pseudo-slit along the North-South direction and covering both galaxies. The pixel-scale on the vertical axis is 0.29″ per pixel. Visible are the lines: Lyα (ν_{rest} = 1215.7 Å), NV (ν_{rest} = 1240 Å), CII (ν_{rest} = 1336 Å), SiIV (ν_{rest} = 1400 Å), NIV] (ν_{rest} = 1486 Å), CIV (ν_{rest} = 1549 Å), HeII (ν_{rest} = 1640 Å), OIII] (ν_{rest} = 1663 Å), and NIII] (ν_{rest} = 1750 Å).

Figure 5 shows a 2D spectrum of the Keck data, obtained by putting a pseudo-slit with a width of 5 spaxels (6.75 arcsec) aligned in north-south direction across the Dragonfly Galaxy. The low spatial resolution of the Keck data means that the NE and SW galaxy cannot be distinguished in these Keck data. We detect in total nine emission lines, including Lyα, NV, CII, SiIV, NIV], CIV, HeII, OIII],and NIII. Based on the Keck spectrum, we can classify this AGN as a Type II AGN. Type II AGNs are characterized by a core that is blocked by the torus, producing only narrow emission lines and lacking the very broad lines from the broad-line region that are typically seen in Type I AGN. Figure 5 shows that several of the emission lines (Lyα, He II, and C VI) appear spatially extended. The Lyα emission stretches across a scale of at least $\sim$70 kpc, which is consistent with the $\sim$60 kpc extent of cold molecular gas previously observed in CO (1-0) [Emonts et al., 2015a]. Emission of the He II and [C IV] metal lines is seen across at least $\sim$35 kpc. This shows that there is a rich circumgalactic medium present around the Dragonfly Galaxy, although a full analysis of the circumgalactic gaseous environment of the Dragonfly is beyond the scope of the current paper.

2.4 Discussion

2.4.1 Merging disk galaxies

The ALMA CO (6-5) moment maps show that both the SE and NW components are rotating disk galaxies. The galaxies appear to be connected by a bridge of tidal gas that shows high velocity dispersion in its central region. The presence of this tidal gas connecting NW and SE, along with their small separation ($\sim$4 kpc), confirms these galaxies are in the process of merging.

By comparing previous CO (6-5) and CO (1-0) spectra at lower resolution, Emonts et al. [2015b] found molecular gas with apparently enhanced excitation at the highest velocities ($|v| \geq 250$ km s^{-1}). They speculated that this highest velocity gas may be either part of interacting disks, or molecular gas driven out of the central nuclei by AGN outflows or starbursts. Our new CO (6-5) data confirm that the bulk of this highest velocity gas is part of the rotating, interacting disks in the SE and NW galaxy. Spectra of the CO (6-5) data reveal no evidence for outflows in the region between the galaxies, so we can conclude that the tidal bridge feature with the high velocity dispersion (Figure 2 Middle) is indeed from tidal effects of merging, not AGN or starburst induced outflows.

Furthermore, the center of the NW galaxy contains the highest velocity dispersion in this system and has more chaotic rotation than the SE galaxy. Based on the 8.2 GHz radio continuum image from Pentericci et al. [2000], Emonts et al. [2015b] argued that the NW galaxy must host the radio-loud AGN. Our current data are consistent with this scenario, and suggest that the AGN activity may be related to the high velocity dispersion of the gas in the NW galaxy.

2.4.2 Re-distribution of cold gas: gravitational effects or outflows?

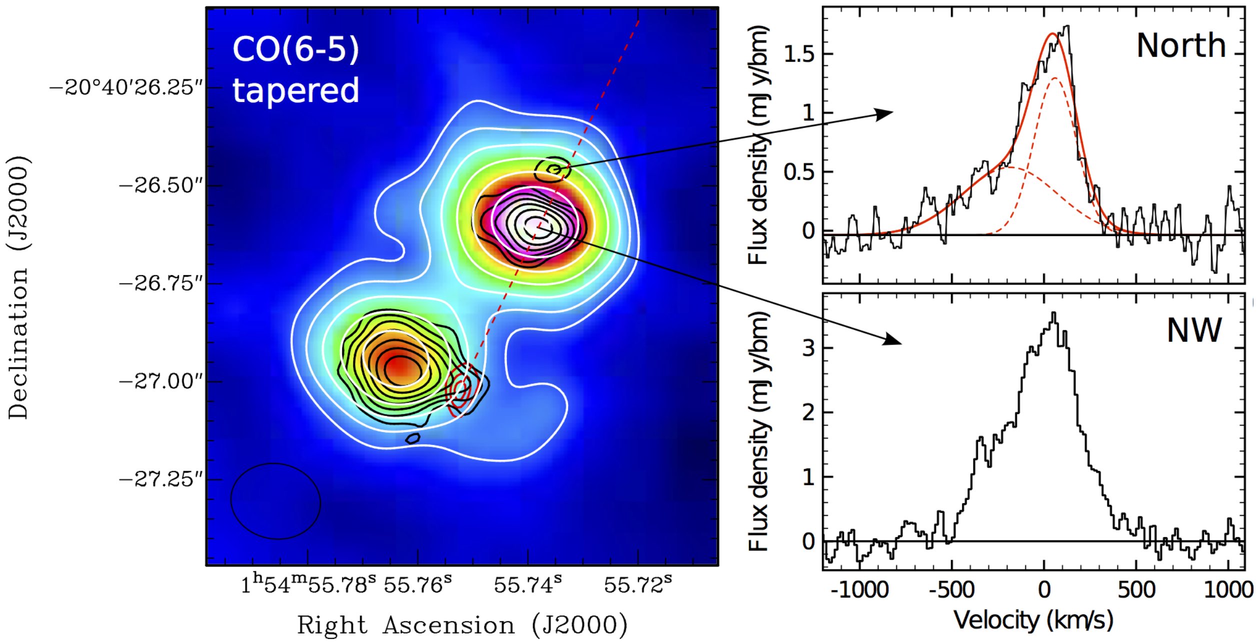

Figure 6: CO (6-5) ALMA image and spectrum with data tapered to a lower resolution. Left: Total intensity image of the CO (6-5) integrated across the velocity range from -750 to +400 $\mathrm{km\,s^{-1}}$. White contours show the total intensity map starting at 4σ and increasing by a factor $\sqrt{2}$, with $\sigma = 0.05$ mJy $\mathrm{bm^{-1}} \times \mathrm{km\,s^{-1}}$. Black contours are the ALMA 237 GHz continuum at full (untapered) resolution from Fig. 2, starting at 5σ and increasing by a factor $\sqrt{2}$, with $\sigma = 15$ μJy $\mathrm{bm^{-1}}$. Red contours are the VLA 43 GHz continuum from Fig. 2.3.2 at levels 0.3, 0.8, 1.3 mJy $\mathrm{bm^{-1}}$. The red dashed line visualizes the axis of the radio source. The synthesized beam of the tapered data is $0.23 \times 0.19''$ (PA 81°), as indicated with the ellipse in the bottom-left corner of the image. Right: spectra of the NW galaxy (bottom) and a region north of the NW galaxy that corresponds to a weak source of ALMA continuum emission (top). For clarification, a Hanning smoothing has been applied to the spectra. The spectrum of the NW region is complex (see Emonts et al. [2015b]), while the spectrum north of the galaxy can be fitted with two Gaussian functions (red lines). The two spectra are not entirely mutually independent, but suggest the presence of an outflow component.

In Sect. 2.4.1, we saw that the bulk of the gas at the highest velocities is part of the rotating disks or tidal debris from the gravitational interaction between them. However, having confirmed that NW hosts a radio-loud AGN and propagating radio jet, we may expect to see some interaction between the jet and molecular gas along the radio axis. The CO (6-5) emission revealed only one potential AGN outflow candidate in the northern region of the NW galaxy, which was best revealed after tapering the data to a lower resolution. Figure 6 (right) shows the spectra corresponding to the center region of NW (bottom right) and northern region of NW (top right). The spectrum taken north of the center of the NW galaxy along the radio axis appears to have a broad, blueshifted wing to the CO profile. A blue wing may also be present in the spectrum taken against the center of the galaxy, but it does not extend as far into the blue and is part of more complex central gas kinematics [Emonts et al., 2015b]. The broad blueshifted wing of the spectrum may be indicative of a blueshifted AGN or starburst outflow, however further analysis is needed to determine if this is in fact an outflow associated with the radio jet. If a blueshifted outflow can be confirmed to be located in the northern region of the NW galaxy and associated with either the northern jet or a central starburst, then the most likely scenario is that the northern jet is the approaching jet and the southern jet is receding.

2.4.3 Jet-disk interaction

The 43 GHz observations conducted by the VLA detected a radio hot spot on the western edge of the SE galaxy. This hot spot appears to be aligned along the central axis of the radio jet (Fig. 2.3.2). Based on this alignment and our conclusion that NW hosts the radio-loud AGN, we theorize that the interaction of the southern jet with the gas and dust in the disk of the SE galaxy is causing the radio emission to brighten up at the location of the 43 GHz detection.

Detection of the potential blueshifted outflow discussed in Sect. 2.4.2 may further support this scenario through the assumed geometry of the system. If the southern jet is receding and interacting with the SE disk, then SE must be oriented behind NW in our plain of view. This scenario would have unique consequences on our interpretation of this system. At high redshifts, the brightening of the receding jet cannot be explained by Doppler Boosting, which causes intrinsic brightening of the jet only for relativistic particles moving towards us. This would suggest that the southern jet brightens only because of its interaction with the SE galaxy, which would boost the radio flux of the system. If this is the case, then the Dragonfly Galaxy may not be as intrinsically radio bright as previously thought, making it an "imposter" radio galaxy in the high-z universe. Several steps are necessary before we can confirm this theory, but new ALMA Cycle 6 data may provide answers to these questions (see Section 3.1 for more information on future work).

2.5 Conclusion

We presented new ALMA and VLA data of CO(6-5), dust and synchrotron emission in the enigmatic Dragonfly Galaxy with a spatial resolution of $\sim$1 kpc. Our main conclusions are:

- The presence of rotating discs and tidal debris in a gaseous bridge connecting the two galaxies suggest that gravitational effects are the main cause for the previously reported high rates of gas displacement in this system.
- The high velocity dispersion of CO (6-5) in the central region of NW, combined with the detection of hot-spots from the jet and counter-jet in our VLA data, is consistent with the NW galaxy hosting the radio-loud AGN.
- An interaction of the radio jet with the disk of the SE galaxy is the likely cause for the jet to brighten at the hot-spot.
- The Keck spectrum with rest-frame UV lines identifies the Dragonfly as a Type II AGN.

Our results suggest that, despite the presence of a Type II AGN, we only see the Dragonfly Galaxy as a powerful radio galaxy due to an interaction between the radio jet and the disk of the secondary galaxy. This chance interaction provides a unique snapshot of the evolutionary history of galaxies in which a major-merger event coincides with radio activity. More research is needed to identify how common these systems may be in the high-z universe. Future work on the Dragonfly Galaxy will further investigate the nature of radio activity and feedback in this system.

3 Chapter 3

3.1 Future Work

Current analysis of the Cycle 4 ALMA, new high resolution VLA data, and Keck spectroscopy has already revealed interesting results about the Dragonfly Galaxy including the presence of rotating disks, tidal gas from the interaction of the merging galaxies, determination of the AGN host galaxy and Type II AGN, and a likely jet-disk interaction causing a radio bright spot in the VLA data. However, there is still much left to investigate in the current data as well as a future data set. The Chapter 2 results section on the Keck data shows only the most preliminary analysis of the Keck spectrum and optical data. While we have identified nine emission lines and extended Lyman-alpha, Helium II, and Carbon IV, we have yet to determine line ratios and retrieve the fluxes which will allow us to create line diagnostic diagrams to learn more about the energy sources creating the emission lines. We also intend to conduct Gaussian fits for the spectra as well as more closely investigate the kinematics of the optical data to get a more complete picture of the larger gaseous environment surrounding the system. Our collaborator Dr. Montserrat Villar-Martin, who is an expert on AGN spectra, may also provide further insight on Type II AGNs in these high-z systems.

The ALMA Cycle 4 data of CO (6-5) also revealed a possible candidate for a blueshifted AGN outflow, located north of the NW galaxy. While we do see a broadening of the blueshifted wing in Fig. 7 as you move northward from the center of NW, this is not yet confirmed to be a separate feature from the gas kinematics of the rotating disk. The ALMA Cycle 4 data does not have the resolution and sensitivity needed to conduct a detailed analysis on the potential outflow. Fortunately, we have new ALMA Cycle 6 data on the Dragonfly Galaxy with higher resolution and sensitivity that will allow us to study the outflow in more detail. As discussed in Section 2.3.3, detection of a blueshifted AGN outflow aligning with the northern jet and the likely jet-disk interaction detected by the VLA would allow us to determine the geometry of the system. SW would have to be oriented behind NW to make the redshifted jet interaction with its disk possible. While it is possible that there may be alternative explanations for the brightening of the radio jet at the 43 GHz detection, the alignment of the hot-spot with the outer edge of the disk of the SE galaxy makes the jet-disk interaction the most plausible current explanation. The ALMA Cycle 6 data may provide a better understanding of this interaction by examining this region for kinematic evidence of a jet-disk interaction.

3.1.1 ALMA Cycle 6 Data

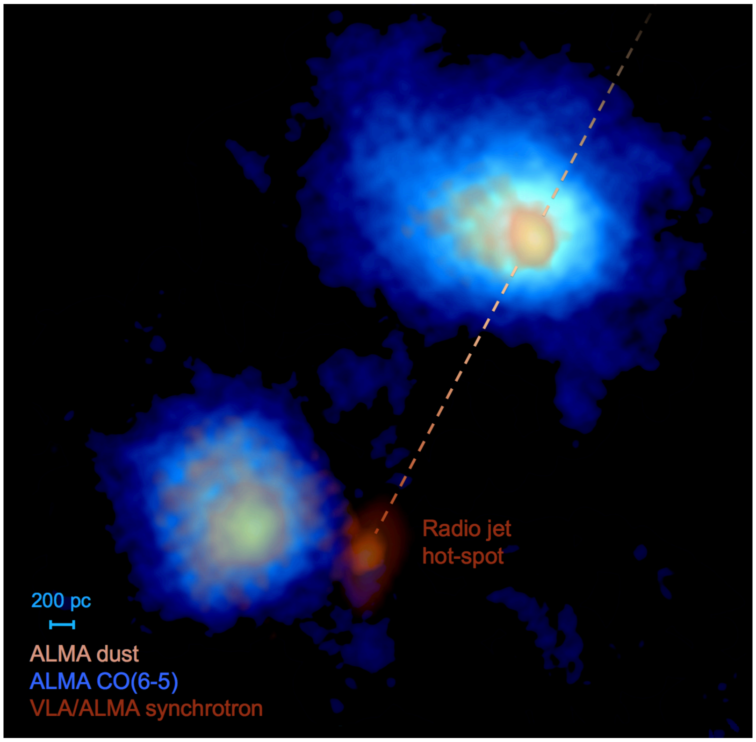

Figure 7: Artist impression of the Dragonfly Galaxy from preliminary imaging from the ALMA Cycle 6 data.

Figure 7 shows a preliminary sample image of the new ALMA Cycle 6 data with the radio axis of the jet and radio hot spot overlaid. With its higher resolution and sensitivity, ALMA Cycle 6 is able to detect CO (6-5) emission in the Dragonfly Galaxy in greater detail which may provide a better understanding of the kinematics of the outflow and also within the tidal bridge connecting the two merging galaxies. In addition, the cycle 6 data may also provide the resolution and sensitivity needed to examine the direction of gas flows in this system. We hope to also spatially map out the outflow candidate by separating the broad and narrow components of the outflow spectrum shown in Fig. 6 to determine the direction of the outflow relative to the center of NW. Preliminary investigation of the ALMA Cycle 6 data by Dr. Emonts seems to support the current story, although the full analysis will be conducted at a later time and then incorporated into a future paper that I will be involved with.

3.1.2 Unanswered Questions

The z=2-4 epoch represents an important period in galaxy evolution characterized by major merger events, massive galaxy formation, extreme starbursts, and AGN activity. The Dragonfly Galaxy provides an excellent laboratory for studying massive galaxy formation at high redshift due to its bright radio and IR luminosity. While there are many high-z radio galaxies, it is unclear how populated this regime is with extreme systems like the Dragonfly. If the Dragonfly Galaxy is in fact a radio imposter due to the chance alignment between the radio axis and the disk of the companion galaxy, it would be interesting to further explore how common jet-disk interactions are in merging systems that boost the radio flux of the system. This would involve an extensive investigation to both identify merging radio-loud systems and explore their molecular gas kinematics. Further studies on these high-z radio galaxies may also help to answer outstanding questions about AGN and jets such as what causes some AGN to produce more powerful jets than others, or no jets at all? Even more fundamentally, what makes an AGN turn on?

Systems like the Dragonfly Galaxy may also help to answer fundamental questions about the relationship between AGN activity and merging. The gas redistribution due to merging has been proposed to trigger mass accretion onto the supermassive black hole, powering the AGN. In some radio-loud systems, we see powerful AGN outflows produced by the propagating jets that originate from the AGN [e.g., Nesvadba et al., 2017]. These AGN-induced outflows can play a large role in gas redistribution within the circumgalactic environment of the galaxy and can act as a feedback mechanism by inducing or quenching star formation. If there are AGN outflows in the Dragonfly Galaxy, these do not seem to produce an extreme degree of gas displacement in the Dragonfly's galactic environment compared to tidal interactions from merging. Is this because the Dragonfly does not in fact host an intrinsically powerful radio jet, do the outflows only occur in warmer ionized gas, or are we unable to detect the scale of the potential AGN outflows in the system with the current resolution of the ALMA Cycle 4 data? A continued search for outflows in the Dragonfly Galaxy will not only help to reveal a better understanding of the kinematics of this system, but may also shed light on the role of AGN feedback in driving galaxy evolution.

References

L. Pentericci, W. Van Reeven, C. L. Carilli, H. J. A. Röttgering, and G. K. Miley. VLA radio continuum observations of a new sample of high redshift radio galaxies. , 145:121–159, Jul 2000. doi: 10.1051/aas:2000104.

L. Pentericci, P. J. McCarthy, H. J. A. Röttgering, G. K. Miley, W. J. M. van Breugel, and R. Fosbury. NICMOS Observations of High-Redshift Radio Galaxies: Witnessing the Formation of Bright Elliptical Galaxies? , 135(1):63–85, Jul 2001. doi: 10.1086/321781.

G. Drouart, C. De Breuck, J. Vernet, N. Seymour, M. Lehnert, P. Barthel, F. E. Bauer, E. Ibar, A. Galametz, M. Haas, N. Hatch, J. R. Mullaney, N. Nesvadba, B. Rocca-Volmerange, H. J. A. Röttgering, D. Stern, and D. Wylezalek. Rapidly growing black holes and host galaxies in the distant Universe from the Herschel Radio Galaxy Evolution Project. , 566:A53, Jun 2014. doi: 10.1051/0004-6361/201323310.

B. H. C. Emonts, M. Y. Mao, A. Stroe, L. Pentericci, M. Villar-Martín, R. P. Norris, G. Miley, C. De Breuck, G. A. van Moorsel, and et al. A CO-rich merger shaping a powerful and hyperluminous infrared radio galaxy at z = 2: the Dragonfly Galaxy. , 451(1):1025–1035, Jul 2015a. doi: 10.1093/mnras/stv930.

B. H. C. Emonts, C. De Breuck, M. D. Lehnert, J. Vernet, B. Gullberg, M. Villar-Martín, N. Nesvadba, G. Drouart, R. Ivison, N. Seymour, D. Wylezalek, and P. Barthel. The Dragonfly Galaxy. II. ALMA unveils a triple merger and gas exchange in a hyper-luminous radio galaxy at z = 2. , 584:A99, Dec 2015b. doi: 10.1051/0004-6361/201526090.

Sophie Lebowitz. The Dragonfly Galaxy: Searching for Outflows in a Radio-loud Triple Merger. In *American Astronomical Society Meeting Abstracts #233*, volume 233 of *American Astronomical Society Meeting Abstracts*, page 145.04, January 2019.

H. J. A. Roettgering, M. Lacy, G. K. Miley, K. C. Chambers, and R. Saunders. Samples of ultra-steep spectrum radio sources. , 108:79–141, Nov 1994.

K. C. Chambers, G. K. Miley, W. J. M. van Breugel, and J.-S. Huang. Ultra–Steep-Spectrum Radio Sources. I. 4C Objects. *ApJS*, 106:215, October 1996. doi: 10.1086/192337.

C. L. Carilli, H. J. A. Röttgering, R. van Ojik, G. K. Miley, and W. J. M. van Breugel. Radio Continuum Imaging of High-Redshift Radio Galaxies. , 109(1):1–44, Jan 1997. doi: 10.1086/312973.

George Miley and Carlos De Breuck. Distant radio galaxies and their environments. , 15(2):67–144, Feb 2008. doi: 10.1007/s00159-007-0008-z.

Nick Seymour and SHzRG Collaboration. The Massive Hosts of Radio Galaxies Across Cosmic Time. In *American Astronomical Society Meeting Abstracts #210*, volume 210 of *American Astronomical Society Meeting Abstracts*, page 32.05, May 2007.

Carlos De Breuck, Nick Seymour, Daniel Stern, S. P. Willner, P. R. M. Eisenhardt, G. G. Fazio, Audrey Galametz, Mark Lacy, Alessandro Rettura, Brigitte Rocca-Volmerange, and Joël Vernet. The Spitzer High-redshift Radio Galaxy Survey. , 725(1):36–62, Dec 2010. doi: 10.1088/0004-637X/725/1/36.

B. Rocca-Volmerange, G. Drouart, C. De Breuck, J. Vernet, N. Seymour, D. Wylezalek, M. Lehnert, N. Nesvadba, and M. Fioc. Starburst and old stellar populations in the z 3.8 radio galaxies 4C 41.17 and TN J2007-1316. , 429(4):2780–2790, Mar 2013. doi: 10.1093/mnras/sts413.

Peter Barthel, Martin Haas, Christian Leipski, and Belinda Wilkes. Extreme Host Galaxy Growth in Powerful Early-epoch Radio Galaxies. , 757(2):L26, Oct 2012. doi: 10.1088/2041-8205/757/2/L26.

G. Drouart, B. Rocca-Volmerange, C. De Breuck, M. Fioc, M. Lehnert, N. Seymour, D. Stern, and J. Vernet. Disentangling star formation and AGN activity in powerful infrared luminous radio galaxies at 1 < z < 4. , 593:A109, Sep 2016. doi: 10.1051/0004-6361/201526880.

Belinda J. Wilkes, Joanna Kuraszkiewicz, Martin Haas, Peter Barthel, Christian Leipski, S. P. Willner, D. M. Worrall, Mark Birkinshaw, Robert Antonucci, M. L. N. Ashby, Rolf Chini, G. G. Fazio, Charles Lawrence, Patrick Ogle, and Bernhard Schulz. Revealing the Heavily Obscured Active Galactic Nucleus Population of High-redshift 3CRR Sources with Chandra X-Ray Observations. , 773(1):15, Aug 2013. doi: 10.1088/0004-637X/773/1/15.

M. Villar-Martín, L. Binette, and R. A. E. Fosbury. The nature of the extreme kinematics in the extended gas of high redshift radio galaxies. , 346:7–12, Jun 1999.

N. P. H. Nesvadba, C. De Breuck, M. D. Lehnert, P. N. Best, and C. Collet. The SINFONI survey of powerful radio galaxies at z 2: Jet-driven AGN feedback during the Quasar Era. , 599:A123, Mar 2017. doi: 10.1051/0004-6361/201528040.

L. Pentericci, H. J. A. Roettgering, G. K. Miley, C. L. Carilli, and P. McCarthy. The radio galaxy 1138-262 at z=2.2: a giant elliptical galaxy at the center of a proto-cluster? , 326:580–596, Oct 1997.

B. P. Venemans, H. J. A. Röttgering, G. K. Miley, W. J. M. van Breugel, C. de Breuck, J. D. Kurk, L. Pentericci, S. A. Stanford, R. A. Overzier, S. Croft, and H. Ford. Protoclusters associated with z 2 radio galaxies . I. Characteristics of high redshift protoclusters. *A&A*, 461:823–845, January 2007. doi: 10.1051/0004-6361:20053941.

N. A. Hatch, R. A. Overzier, J. D. Kurk, G. K. Miley, H. J. A. Röttgering, and A. W. Zirm. The growth and assembly of a massive galaxy at z ~2. , 395(1):114–125, May 2009. doi: 10.1111/j.1365-2966.2009.14525.x.

Audrey Galametz, Daniel Stern, Carlos De Breuck, Nina Hatch, Jack Mayo, George Miley, Alessand ro Rettura, Nick Seymour, S. Adam Stanford, and Joël Vernet. The Mid-infrared Environments of High-redshift Radio Galaxies. , 749(2):169, Apr 2012. doi: 10.1088/0004-637X/749/2/169.

D. Wylezalek, A. Galametz, D. Stern, J. Vernet, C. De Breuck, N. Seymour, M. Brodwin, P. R. M. Eisenhardt, A. H. Gonzalez, N. Hatch, M. Jarvis, A. Rettura, S. A. Stanford, and J. A. Stevens. Galaxy Clusters around Radio-loud Active Galactic Nuclei at 1.3 z 3.2 as Seen by Spitzer. *ApJ*, 769:79, May 2013. doi: 10.1088/0004-637X/769/1/79.

H. Dannerbauer, J. D. Kurk, C. De Breuck, D. Wylezalek, J. S. Santos, Y. Koyama, N. Seymour, M. Tanaka, and et al. An excess of dusty starbursts related to the Spiderweb galaxy. , 570:A55, Oct 2014. doi: 10.1051/0004-6361/201423771.

Allison W. S. Man, Matthew D. Lehnert, Joël D. R. Vernet, Carlos De Breuck, and Theresa Falkendal. Quenching by gas compression and consumption. A case study of a massive radio galaxy at z = 2.57. , 624:A81, Apr 2019. doi: 10.1051/0004-6361/201834542.

Theresa Falkendal, Carlos De Breuck, Matthew D. Lehnert, Guillaume Drouart, Joël Vernet, Bjorn Emonts, Minju Lee, Nicole P. H. Nesvadba, Nick Seymour, Matthieu Béthermin, Sthabile Kolwa, Bitten Gullberg, and Dominika Wylezalek. Massive galaxies on the road to quenching: ALMA observations of powerful high redshift radio galaxies. , 621:A27, Jan 2019. doi: 10.1051/0004-6361/201732485.

G. Drouart and T. Falkendal. MR-MOOSE: an advanced SED-fitting tool for heterogeneous multi-wavelength data sets. , 477(4):4981–5000, Jul 2018. doi: 10.1093/mnras/sty831.

B. H. C. Emonts, I. Feain, M. Y. Mao, R. P. Norris, G. Miley, R. D. Ekers, M. Villar-Martín, H. J. A. Röttgering, E. M. Sadler, G. Rees, R. Morganti, D. J. Saikia, T. A. Oosterloo, J. B. Stevens, and C. N. Tadhunter. Molecular CO(1-0) Gas in the z ~2 Radio Galaxy MRC 0152-209. , 734(1): L25, Jun 2011. doi: 10.1088/2041-8205/734/1/L25.

B. H. C. Emonts, R. P. Norris, I. Feain, M. Y. Mao, R. D. Ekers, G. Miley, N. Seymour, H. J. A. Röttgering, M. Villar-Martín, and et al. CO(1-0) survey of high-z radio galaxies: alignment of molecular halo gas with distant radio sources. , 438(4):2898–2915, Mar 2014. doi: 10.1093/mnras/stt2398.

E. L. Wright. A Cosmology Calculator for the World Wide Web. , 118(850):1711–1715, Dec 2006. doi: 10.1086/510102.